

Search for $D^0 - \bar{D}^0$ mixing using semileptonic decays at Belle

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A search for mixing in the neutral D meson system has been performed using semileptonic $D^0 \rightarrow K^{(*)-} e^+ \nu$ decays. Neutral D mesons from $D^{*+} \rightarrow D^0 \pi^+$ decays are used; the flavor at production is tagged by the charge of the slow pion. The measurement is performed using 253 fb^{-1} of data recorded by the Belle detector. From the yield of right-sign and wrong-sign decays arising from non-mixed and mixed events, respectively, we estimate the upper limit of the time-integrated mixing rate to be $r_D < 1.0 \times 10^{-3}$ at 90% C.L.

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I. INTRODUCTION

The phenomenon of mixing has been observed in the $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ systems, but not yet in the $D^0 - \bar{D}^0$ system. The parameters used to characterize $D^0 - \bar{D}^0$ mixing are $x = \Delta m / \bar{\Gamma}$ and $y = \Delta \Gamma / 2\bar{\Gamma}$, where Δm and $\Delta \Gamma$ are the differences in mass and decay width between the two neutral charmed meson mass eigenstates, and $\bar{\Gamma}$ is the mean decay width. The mixing rate within the Standard Model is expected to be small [1]: the largest predicted values, including the impact of long distance dynamics, are of order $x \lesssim y \sim 10^{-3} - 10^{-2}$. Observation of a mixing rate significantly larger than predicted would indicate either new physics (enhanced x) or insufficient understanding of long distance effects (larger y).

For $x, y \ll 1$ and negligible CP violation, the time-dependent mixing probability for semileptonic D^0 decays is [2]

$$\mathcal{P}(D^0 \rightarrow \bar{D}^0 \rightarrow X^+ \ell^- \bar{\nu}_\ell) \propto r_D t^2 e^{-\Gamma t}, \quad (1)$$

where r_D is the ratio of the time-integrated mixing to the time-integrated non-mixing probability:

$$r_D = \frac{\int_0^\infty dt \mathcal{P}(D^0 \rightarrow \bar{D}^0 \rightarrow X^+ \ell^- \bar{\nu}_\ell)}{\int_0^\infty dt \mathcal{P}(D^0 \rightarrow X^- \ell^+ \nu_\ell)} \approx \frac{x^2 + y^2}{2}. \quad (2)$$

In this paper we present a search for $D^0 - \bar{D}^0$ mixing using semileptonic decays of charmed mesons. The flavor of a neutral D meson at production is determined from the charge of the accompanying slow pion (π_s) in the $D^{*+} \rightarrow D^0 \pi_s^+$ decay [3]. We reconstruct the D^0 as $D^0 \rightarrow K^{(*)-} e^+ \nu_e$ and identify its flavor at the time of decay from the charge correlation of the kaon and the electron. We search for mixing by reconstructing the “wrong

sign” (WS) decay chain, $D^{*+} \rightarrow D^0 \pi_s^+$, $D^0 \rightarrow \bar{D}^0$, $\bar{D}^0 \rightarrow K^{(*)+} e^- \bar{\nu}_e$, which results in a WS charge combination of the three particles used to reconstruct the candidate. The non-mixed process results in a “right sign” (RS) charge combination, $\pi_s^+ K^- e^+$. In contrast to hadronic decays, the WS charge combinations can occur only through mixing, and r_D can be obtained directly as the ratio of WS to RS signal events.

We make no attempt to reconstruct K^{*-} mesons. We treat charged daughter particles (K^- or π^-) as if they were the direct daughters of the D^0 , omitting the accompanying neutral particle. A small contribution from $D^0 \rightarrow \rho^- e^+ \nu_e$ and $D^0 \rightarrow \pi^- e^+ \nu_e$ decays, due to charged pions surviving the kaon selection, is included in the analysis.

We measure r_D in a 253 fb^{-1} data sample recorded by the Belle detector at the KEKB asymmetric-energy $e^+ e^-$ collider [4], at a center-of-mass (cms) energy of about 10.6 GeV. The Belle detector [5] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). Two different inner detector configurations were used. The first 140 fb^{-1} of data were taken using a 2.0 cm radius beampipe and a 3-layer silicon vertex detector, and the subsequent 113 fb^{-1} were taken using a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber [6].

Simulated events are generated by the QQ generator and processed with a full simulation of the Belle detector, using the GEANT package [7]. To simulate mixed D meson decays we use generic (non-mixed) Monte Carlo (MC) events and appropriately reweight the proper decay time distribution.

II. SELECTION AND RECONSTRUCTION

For π_s^+ candidates we consider tracks with: momentum $p < 600 \text{ MeV}/c$; projections of the impact parameter with respect to the interaction point in the radial and beam directions $dr < 1 \text{ cm}$ and $|dz| < 2 \text{ cm}$, respectively; and electron identification likelihood ratio, based on the information from the CDC, ACC and ECL [8], $\mathcal{L}_e < 0.1$. Electron candidates are required to have $p > 600 \text{ MeV}/c$ and $\mathcal{L}_e > 0.95$. Kaon candidates are chosen from the remaining tracks in the event with $p > 800 \text{ MeV}/c$ and $\mathcal{L}(K^\pm)/(\mathcal{L}(K^\pm) + \mathcal{L}(\pi^\pm)) > 0.5$, where $\mathcal{L}(K^\pm, \pi^\pm)$ is the likelihood that a given track is a K^\pm or a π^\pm based on information from the TOF, CDC and ACC. Charged pions originating from semileptonic $D^0 \rightarrow \pi^- e^+ \nu_e$ decays that pass the kaon selection criteria are treated as kaons and assigned the kaon mass. According to MC simulation, this selection retains about 58% (43%, 52%) of signal slow pions (electrons, kaons), and at this stage about 13% (5%, 44%) of the selected π_s (e , K) candidates are misidentified.

The variable used to isolate the signal events is $\Delta M = M(\pi_s K e \nu_e) - M(K e \nu_e)$, where $M(\pi_s K e \nu_e)$ and $M(K e \nu_e)$ are the invariant masses of the selected charged particles and reconstructed neutrino (see below), with and without the slow pion.

We require the cms momentum of the kaon-electron system to be $p_{\text{cms}}(Ke) > 2 \text{ GeV}/c$ to reduce the combinatorial background and the background from $B\bar{B}$ events, and to improve the resolution in ΔM . To further suppress the contribution of $B\bar{B}$ events, we require the ratio of the second to the zeroth Fox-Wolfram moments, known as R_2 , to be greater than 0.2 [9].

Background from $D^0 \rightarrow K^- \pi^+$ decay is suppressed by requiring the invariant mass of the K - e system to satisfy $M(Ke) < 1.82 \text{ GeV}/c^2$. Background from $D^0 \rightarrow K^- K^+$ decay is effectively reduced by the requirement $|M(KK) - m_{D^0}| > 10 \text{ MeV}/c^2$, where $M(KK)$ is the K - e invariant mass, calculated using the kaon mass for both tracks.

The background from photon conversions, where the e^- and e^+ are taken to be the electron and slow pion candidates, is suppressed by requiring $M(e^+ e^-) > 150 \text{ MeV}/c^2$, where $M(e^+ e^-)$ is the invariant mass of the $\pi_s^+ e^-$ system with the electron mass assigned to the pion. A further search for an additional e^\pm with charge opposite to that of the electron (slow pion) candidate in the D^0 (D^{*+}) decay is performed in each event.

Again, candidates with $M(e^+ e^-)$ below $150 \text{ MeV}/c^2$ are rejected.

The first approximation to the neutrino four-momentum is calculated from four-momentum conservation:

$$P_\nu = P_{\text{cms}} - P_{\pi_s K e} - P_{\text{rest}}, \quad (3)$$

where P_{cms} denotes the cms four-momentum of the $e^+ e^-$ system, $P_{\pi_s K e}$ the cms four-momentum of the π_s - K - e combination, and P_{rest} the cms four-momenta of all remaining charged tracks and photons in the event. The ΔM resolution is significantly improved by applying two kinematic constraints to correct P_{rest} . First, events with $-4 \text{ GeV}^2/c^4 < M(\pi_s K e \nu)^2 < 36 \text{ GeV}^2/c^4$ are selected and the magnitude of P_{rest} is rescaled by a factor x such that $M(\pi_s K e \nu)^2 = (P_{\text{cms}} - x P_{\text{rest}})^2 \equiv m_{D^{*\pm}}^2$, with $m_{D^{*\pm}}$ fixed to its nominal value [10]. Next, only events with $-2 \text{ GeV}^2/c^4 < M_\nu^2 < 0.5 \text{ GeV}^2/c^4$ are retained and the direction of the three-momentum \vec{p}_{rest} is corrected in order to yield $M_\nu^2 \equiv 0$. The correction rotates \vec{p}_{rest} in the plane determined by the vectors \vec{p}_{rest} and $\vec{p}_{\pi_s K e}$.

The mass difference ΔM is then calculated using this reconstructed neutrino four-momentum. The full width at half maximum (FWHM) of the ΔM peak in MC simulated $D^0 \rightarrow K^- e^+ \nu$ events is found to be $7 \text{ MeV}/c^2$. Events with $\Delta M < 0.18 \text{ GeV}/c^2$ are retained for further analysis.

According to MC simulation, the $D^0 \rightarrow K^{*-} e^+ \nu_e$, $\rho^- e^+ \nu_e$, and $\pi^- e^+ \nu_e$ modes have ΔM distributions similar to that from $D^0 \rightarrow K^- e^+ \nu_e$ decay, but with a larger FWHM. The charge correlation is preserved if the slow pion decays into a muon, and the muon is taken as the slow pion candidate. These decays will be referred to as “associated signal” decays. Their fraction in the reconstructed MC signal sample is $14.9 \pm 0.1\%$, with the quoted error being due to MC statistics only.

According to MC, the backgrounds for both RS and WS decays consist mainly of combinatorial background (98.4% and 98.0%, respectively). In order to minimize systematic uncertainties, we model the shape of this background using data, following a method validated with MC events. We use candidates with the unphysical sign combinations $\pi_s^+ K^- e^-$ and $\pi_s^+ K^+ e^+$ to model the combinatorial background in the RS sample. In the WS sample this background is mainly due to random π_s^+ candidates combined with the selected kaon and electron candidates, and is modelled by combining π_s^+ and $(K^- + e^+)$ candidates from different events. The correlated background (1.6% in the RS, 2.0% in the WS sample) arises from a true π_s^+ from a D^{*+} decay combined with true or misidentified K and e candidates, both (in the RS sample) or at least one of them (WS sample) from the corresponding D^0 decay. This background is described using MC.

Figure 1 shows the ΔM distribution for RS events. We perform a binned maximum likelihood fit to the distri-

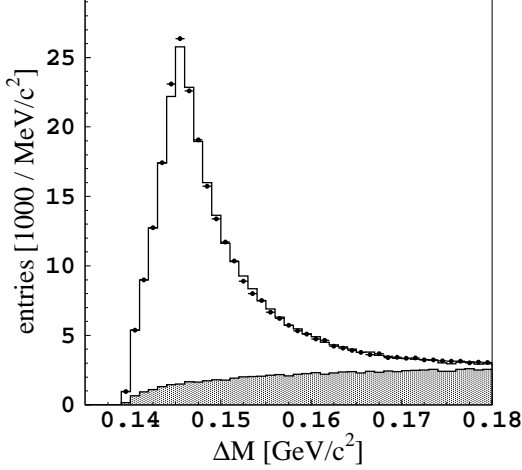


FIG. 1: ΔM distribution for RS events. The data (background) is represented by points (hatched histogram), and the result of the binned maximum likelihood fit by the solid line.

bution, maximizing

$$\mathcal{L} = \prod_{i=1}^{N_{\text{bin}}} \frac{e^{-\mu(\Delta M_i)} \times (\mu(\Delta M_i))^{N_i}}{N_i!}, \quad (4)$$

where N_i is the number of entries in the i -th bin and $\mu(\Delta M_i)$ is the expected number of events in this bin, given by

$$\mu(\Delta M_i) = \mathcal{N}[f_s P_s(\Delta M_i) + (1 - f_s) P_b(\Delta M_i)]. \quad (5)$$

P_s (P_b) is the signal (background) ΔM distribution obtained from MC (as described above); f_s and \mathcal{N} are the signal fraction and the overall normalization, respectively, and are free parameters in the fit. The hatched histogram in Fig. 1 shows the fitted background contribution. The fitted signal fraction is $f_s = 73.4 \pm 0.1\%$ and the number of RS signal events is $N_{\text{RS}}^{\text{tot}} = 229\,452 \pm 597$.

We increase the sensitivity to $D^0 - \bar{D}^0$ mixing by exploiting the measurement of the D^0 proper decay time. The decay time is evaluated using the measured momentum of the meson and the distance from the e^+e^- interaction point to the reconstructed D^0 decay K - e vertex. Due to the shape of the KEKB accelerator interaction region, which is narrowest in the vertical (y) direction, the dimensionless proper decay time t_y is calculated as

$$t_y = \frac{m_{D^0}}{c\tau_{D^0}} \frac{y_{\text{vtx}} - y_{\text{IP}}}{p_y}, \quad (6)$$

where p_y is the y component of the D^0 candidate's momentum and y_{vtx} and y_{IP} are the y coordinates of the reconstructed K - e vertex and of the interaction point, respectively. m_{D^0} and τ_{D^0} are the nominal mass and lifetime of D^0 mesons [10].

Mixed and non-mixed processes have different proper decay time distributions: $t^2 e^{-t/\tau_{D^0}}$ and $e^{-t/\tau_{D^0}}$, respectively. In order to calculate the mixing parameter r_D after any selection based on D^0 proper decay time, the ratio of the two types of signal events, $N_{\text{WS}}/N_{\text{RS}}$, must be multiplied by the ratio of their efficiencies, $\epsilon_{\text{RS}}/\epsilon_{\text{WS}}$. The efficiencies are obtained by integrating the convolution of the above proper decay time distributions with the detector resolution function, over the selected t_y interval. As the observed proper decay time distribution is a convolution of the signal and background probability density functions (p.d.f.) with the detector resolution function, the latter is found by performing a binned χ^2 fit to the RS event t_y distribution: $\int_0^\infty dt [f_s e^{-t/\tau_{D^0}} + (1 - f_s)(f_e e^{-t/\tau_{\text{bkg}}} + (1 - f_e)\delta(t))] \times \mathcal{R}(t/\tau_{D^0} - t_y)$. The signal fraction f_s is obtained from the fit to the ΔM distribution. The fraction f_e of the non-prompt background component and its lifetime τ_{bkg} are fixed to the values obtained by fitting the MC background t_y distributions; $\delta(t)$ describes the shape of the prompt background component. The resolution function $\mathcal{R}(t - t_y)$ is described phenomenologically by the sum of three Gaussians and an additional term for badly reconstructed tracks (“outliers”); we obtain the widths and coefficients from the fit.

The ratios $\epsilon_{\text{RS}}/\epsilon_{\text{WS}}$ are given in Table I. The errors are obtained by varying each parameter in the proper decay time fit by $\pm 1\sigma$, repeating the fit and recalculating the ratios; the resulting changes are summed in quadrature. Using this method, the majority of systematic errors due to the imperfect description of the decay time distribution cancel out.

Comparison of the expected t_y distribution for WS signal and background events indicates that the figure-of-merit, defined as $N_{\text{WS}}^{\text{sig}}/\sqrt{N_{\text{WS}}^{\text{bkg}}}$, is optimal for $t_y \geq 1.0$. Events that satisfy this condition are retained for further analysis.

III. FIT AND RESULTS

We extract the RS and WS signal yields separately in six intervals of t_y . The yields are obtained from binned maximum likelihood fits to ΔM , described by Eq. 4; the WS signal distribution is taken to be the same as the RS. The results are shown in Table I and Fig. 2. We obtain the time-integrated mixing probability ratio in the i -th t_y interval, $r_D^i = N_{\text{WS}}^i/N_{\text{RS}}^i \times \epsilon_{\text{RS}}^i/\epsilon_{\text{WS}}^i$, by multiplying the ratio of WS to RS signal events in each interval by the t_y efficiency ratio. The mixing probability is compatible with zero in all proper decay time intervals (see Fig. 3).

The overall r_D follows from a χ^2 fit with a constant to the measured r_D^i values, using a constant:

$$r_D = (0.20 \pm 0.47) \times 10^{-3}. \quad (7)$$

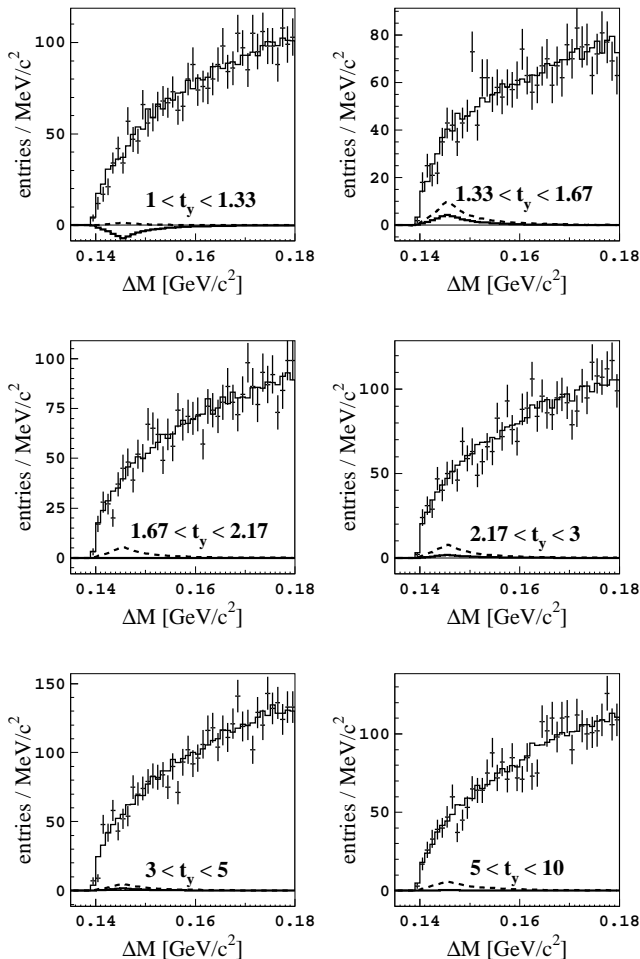


FIG. 2: WS ΔM distributions in six proper decay time intervals for data (points with error bars) and the results of the fit described in the text (solid line). At the bottom of each figure the fitted (expected for $r_D^i = 90\%$ C.L. upper limit) signal yield is plotted as a solid (dashed) line.

The quoted error is statistical only.

IV. SYSTEMATIC UNCERTAINTIES

The experimental procedure was checked using a dedicated MC sample of mixed D^0 decays. These were added in different proportions to the generic MC, which includes both non-mixed D^0 decays and all known types of background decays. The application of the same method used for the data on these samples verified that the reconstructed r_D value reproduces the input value without any significant bias.

The main source of systematic error is the limited statistics of the fitting distributions, predominantly the background distribution in the WS sample. To estimate

TABLE I: The number of fitted signal events in the RS and WS samples, the efficiency ratio $\epsilon_{\text{RS}}^i/\epsilon_{\text{WS}}^i$, and the resulting r_D^i value for each proper decay time interval.

t_y	N_{RS}^i	N_{WS}^i	$\epsilon_{\text{RS}}^i/\epsilon_{\text{WS}}^i$	$r_D^i [10^{-3}]$
1.00-1.33	$18\,742 \pm 166$	-63.7 ± 30.2	1.62 ± 0.11	-5.49 ± 2.63
1.33-1.67	$15\,032 \pm 147$	40.3 ± 29.9	1.14 ± 0.08	3.05 ± 2.27
1.67-2.17	$16\,430 \pm 155$	-1.3 ± 30.6	0.79 ± 0.05	-0.06 ± 1.48
2.17-3.00	$16\,691 \pm 157$	17.0 ± 33.1	0.51 ± 0.03	0.51 ± 1.00
3.00-5.00	$15\,443 \pm 160$	14.7 ± 37.4	0.30 ± 0.01	0.28 ± 0.72
5.00-10.0	$8\,263 \pm 123$	3.0 ± 35.2	0.28 ± 0.02	0.10 ± 1.19

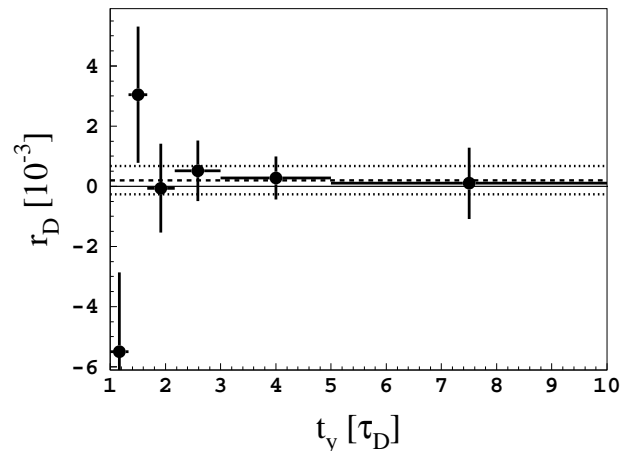


FIG. 3: Measured r_D^i values (points with error bars) in six different proper decay time intervals. The solid (dashed) line shows the null value (the fit to the six r_D^i using a constant). The dotted lines denote the statistical error of the fit.

this uncertainty, we vary the contents of all bins of the RS and WS $P_s(\Delta M)$ and $P_b(\Delta M)$ distributions independently in accordance with each bin's statistical uncertainty, repeat the fit to the RS and WS data, calculate the corresponding r_D^i in each proper decay time interval, and obtain a new r_D value. Repeating the procedure, the obtained distribution of r_D values has a Gaussian shape with a width of 0.12×10^{-3} , which is taken as the systematic error due to the limited statistics of the fitting distributions.

To estimate the systematic uncertainty due to the ΔM binning and the shape of the WS background, the ΔM distributions in each proper decay time interval, originally divided into 45 bins in the range $0.135 \text{ GeV}/c^2 < \Delta M < 0.180 \text{ GeV}/c^2$, are re-binned into 12, 15, 20, 30 and 60 bins in the same range. The fitting procedure is repeated for each set of bins, and the systematic error due to binning is taken as half the difference between the largest and the smallest r_D : $\pm 0.07 \times 10^{-3}$.

According to MC, the majority of the correlated WS background arises from $D^0 \rightarrow K^- \pi^+ \pi^0$ decays. We repeat the WS fits, changing the amount of this background in accordance with the relative error on $\mathcal{B}(D^0 \rightarrow$

$K^-\pi^+\pi^0$). The resulting variation in r_D is $\pm 0.02 \times 10^{-3}$. The same method applied in the fit to the RS sample introduces a negligible variation of the r_D value (less than 0.001×10^{-3}).

We compare the ϵ_{RS}^i values with the corresponding $N_{\text{RS}}^i/N_{\text{RS}}^{\text{tot}}$ ratios. The relative difference between the two is conservatively assigned as the uncertainty on $\epsilon_{\text{RS}}^i/\epsilon_{\text{WS}}^i$, although one expects at least part of the systematic uncertainty to cancel in the efficiency ratio. We reduce the six efficiency ratios simultaneously by this uncertainty and repeat the r_D calculation; we then increase the ratios by this uncertainty, and again recalculate r_D . We quote the difference between the resulting r_D values and the default fit ($\pm 0.02 \times 10^{-3}$) as the systematic error due to an imperfect description of the proper decay time distributions.

The systematic error due to the uncertainty in the associated signal fraction is estimated by varying the fraction and repeating the fitting procedure. Using the errors on the measured branching fractions [10] of the associated signal decay channels, we conservatively vary the amount of associated signal by $\pm 40\%$. We recalculate r_D and compare it to the default r_D value; we quote the difference, 0.002×10^{-3} , as the systematic error from this source.

The quadratic sum of these individual contributions yields a total systematic error of $\pm 0.14 \times 10^{-3}$.

V. CONCLUSION

In summary, we have searched for $D^0 - \bar{D}^0$ mixing in semileptonic D^0 decays. We independently measure the mixing ratios r_D^i in six D^0 proper decay time intervals. By fitting a constant to these six values we obtain the final result

$$r_D = (0.20 \pm 0.47 \pm 0.14) \times 10^{-3}, \quad (8)$$

where the first error is the statistical and the second the systematic uncertainty. As we do not observe a significant number of WS D^0 decays, we obtain an upper limit for the time-integrated mixing rate. We use the Feldman-Cousins approach [11] to calculate the upper limit in the vicinity of the physics region boundary ($r_D \geq 0$). Using the result and the total error in Eq. 8, this yields

$$r_D \leq 1.0 \times 10^{-3} \quad \text{at 90\% C.L.} \quad (9)$$

This result is the most stringent experimental limit on the time-integrated D^0 mixing rate obtained to date from semileptonic D^0 decays [10].

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